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Isomeric state in Bi^{206}

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With 5 figures in the text

ABSTRACT

A half-life of 7.8 ± 0.3 μsec has been measured for the 59.9 keV $E2$ transition in Bi^{203}. Delayed coincidence studies show that all strong gamma rays from the decay of Po^{206} precede the 59.9 keV transition. The spins of the levels in Bi^{206} are discussed.

Introduction

Recently the excited states in Bi^{206}, following from the decay of Po^{206}, were studied at this institute [1]. In the conversion spectra, conversion electrons from a strong $E2$ transition of 59.9 keV energy were observed. From theoretical single proton transition probabilities [2] a lifetime of the order of 10^{-7} sec can be estimated for this transition. For that reason, and based on available coincidence information the 59.9 keV transition was assumed to de-excite the first exicted level in the proposed level scheme of Bi^{206}.

In a search for delayed coincidences between the 286.5 and 59.9 keV transitions using a double lens coincidence beta spectrometer, no delayed coincidences were observed [1]. The result was not considered quite reliable on account of poor statistics due to the low coincidence counting rate and the low detector efficiency.

A determination of the lifetime was, however, desirable, both on account of the theoretical interest in transition probabilities and because it would mean a possibility of determining uniquely the position of the 59.9 keV transition in the decay scheme. The measurements were done with a previously described method, using a multichannel time analyzer [3].

Measurements and results

Since the lifetime was expected to be of the order 10^{-7} sec, a preliminary measurement was done with a coincidence circuit with a resolving time of 2×10^{-7} sec. The actual arrangement is shown in Fig. 1a. Pulses from two scintillation counters, one for detection of gamma rays, and the other for detection of the conversion electrons of the 59.9 keV transition are analyzed in two single channel pulse-height analyzers. After selection of the proper pulse height in each analyzer the pulses are fed to the coincidence unit. A variable delay of maximum 1 μsec can be inserted in each channel.

The gamma rays were detected with an 1″ diameter NaI(Tl) crystal.

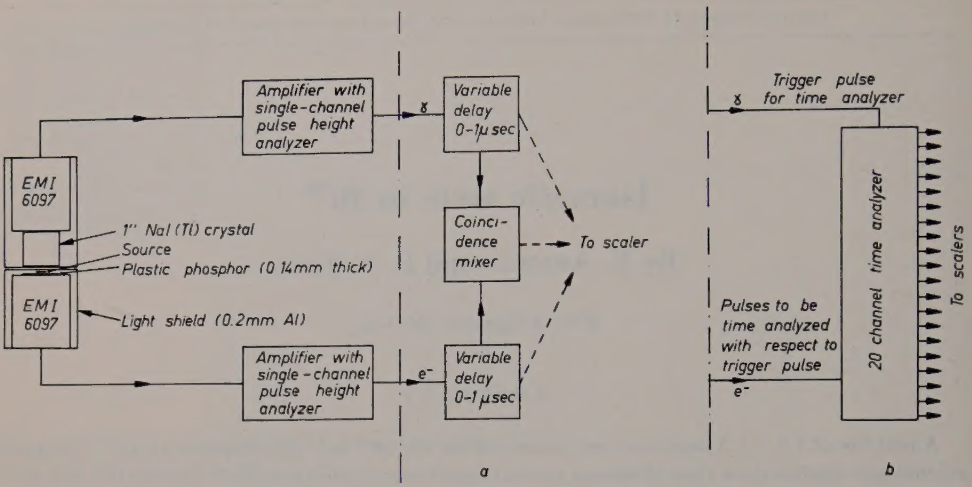
Amplifier with single-channel pulse height analyzer
γ
Variable delay 0-1μ sec
EMI 6097
1" NaI (Tl) crystal
Source
Plastic phosphor (0.14mm thick)
EMI 6097
Light shield (0.2mm Al)
Coincidence mixer
To scaler
Amplifier with single-channel pulse height analyzer
e⁻
Variable delay 0-1 μsec
a
Trigger pulse for time analyzer
γ
20 channel time analyzer
To scalers
Pulses to be time analyzed with respect to trigger pulse
e⁻
b

Fig. 1. Block diagram of the experimental arrangement. In the half-life measurements the coincidence unit (*a*) was substituted by the 20 channel time analyzer (*b*).

According to the L shell conversion coefficients calculated by Rose *et al.* [4] and the experimental L/M ratio [1] the total conversion coefficient is estimated to about 80 for an $E2$ transition of 59.9 keV energy in Bi. The transition is then most suitably detected by its conversion electrons. As electron detector an E.M.I. 6097A photomultiplier with a photosensitivity of 85 $\mu A/L$ and a very thin (0.14 mm) plastic phosphor with an area of about 1 cm^2 was used. The phosphor was made by pressing a thicker sample of UCRL plastic fluor[1] at 100°C. The back side was covered with a thin light-reflecting layer of aluminium in a vacuum evaporation unit. The small thickness of this low density phosphor, while sufficient to stop 100 keV electrons, makes it relatively insensitive to the strong X- and gamma-radiation from the source. The Po^{206} source, prepared by plating on 3 mg/cm^2 silver [1], was placed close to the phosphor with practically no collimation. Fig. 2 shows the pulse-height distribution obtained with this arrangement. The full line is from a freshly prepared Po^{206} source. The dotted line shows the distribution from a 12-day-old source, and shows the growing 96 keV K line of the strong 184.1 keV transition in Pb^{206}. This line was used as an energy check. The Po^{206} 5.2 MeV alpha-ray peak appeared at a place in the pulse-height spectra corresponding to about 13 times higher energy loss in the crystal per photoelectron in the photomultiplier. This is in agreement with the non-linear behaviour of organic crystals [5].

The poor resolution of the electron lines is to be attributed to statistical spread in the small number of photoelectrons resulting from the low energy and the relatively inefficient plastic phosphor. Another contribution comes from scattering and the presence of several L and M lines of different energies. The thermal noise pulses of the photomultiplier come in at approximately $\frac{1}{4}$ of the amplitude in the peak of the 59.9 keV electron distribution.

The delayed coincidence curve shown in Fig. 3 is taken with the e^- channel set to accept the peak of the electron distribution from the 59.9 keV transition, and the

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[1] Obtained from Radiation Lab., Livermore, California.

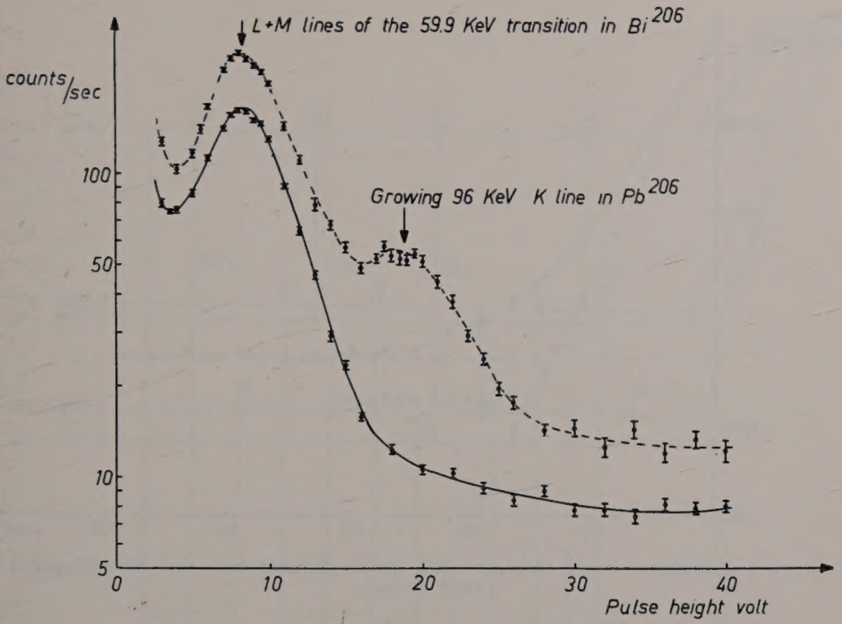

Fig. 2. Scintillation spectra of low energy conversion electrons from Po^{206}, measured with a 0.14 mm thick plastic phosphor. Full line from a freshly plated source; dotted line from a 12-day-old source.

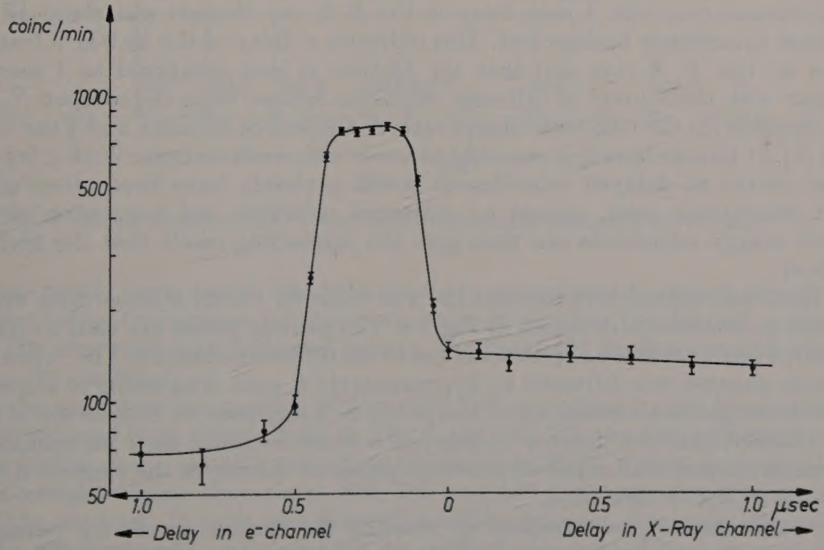

Fig. 3. Delayed coincidence curve obtained with the coincidence unit. Resolving time 0.2 μsec.

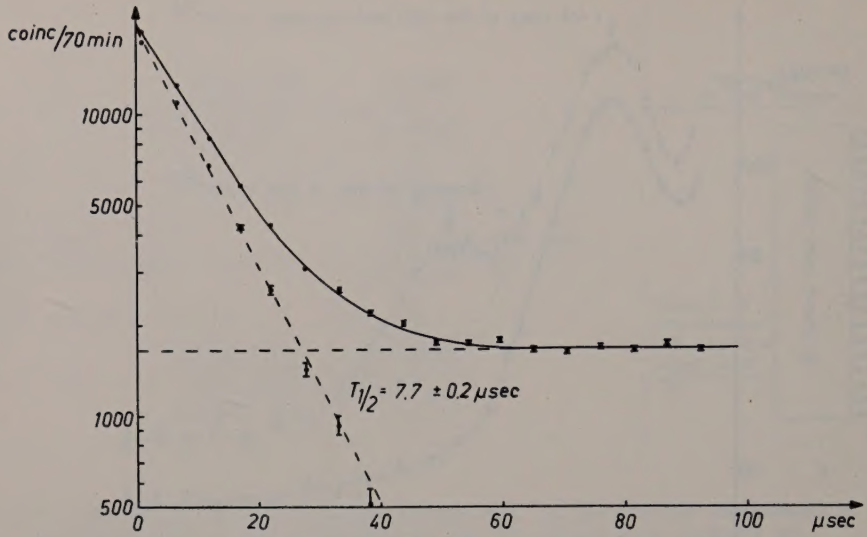

Fig. 4. Delayed coincidence curve obtained with the 20-channel time analyzer, triggered by the Bi *K* X-rays.

gamma channel set to accept the *K* X-ray peak in Bi. In addition to the prompt coincidence peak a surplus of coincidences is seen to exist on that side of the peak which corresponds to delay of the *K* X-ray pulses. The coincidence counting rate is about twice that on the other side, which corresponds to the chance coincidence background N_c, calculable from the resolution t_r and the single counting rates N_{e^-} and N_γ according to $N_c = 2N_{e^-} N_\gamma t_r$. With a weaker source about one-fifth as strong, the coincidence rate with 1 μsec delay in the *K* X-ray channel was about 10 times the chance coincidence background. This indicates a delay of the 59.9 keV transition relative to the *K* X-rays and that the lifetime is long compared to 1 μsec. The behaviour with the sources of different strengths follows from the relation $N_r/N_c \approx 1/\tau N$, where N_r is the true coincidence rate, N the source strength and τ the lifetime ($\tau \gg t_r$) [3]. It follows that it is essential to work with weak sources. With a few times stronger source no delayed coincidences would probably have been observed. The prompt coincidence peak, caused by scattered radiation and conversion electrons of higher energy transitions can then give the misleading result that the lifetime is very short.

The final determination of the half-life was made by the 20-channel time analyzer [3], which is schematically shown in Fig. 1*b*. The gamma pulses are used to start the "channel sweep", while the e^- pulses are fed to the different channels. The "open time" t_k for each channel was adjusted to approximately 6 μsec. The result of a measurement with the gamma counter set to accept the *K* X-ray peak in Bi is shown in Fig. 4. It was checked that the number of delayed coincidences had their maximum when the electron counter was adjusted to accept pulses at the top of the electron distribution of the 59.9 keV transition.

t_k for each channel was checked by starting the channel sweep by pulses from another source, giving pulses unrelated to those accepted in the channels. For this

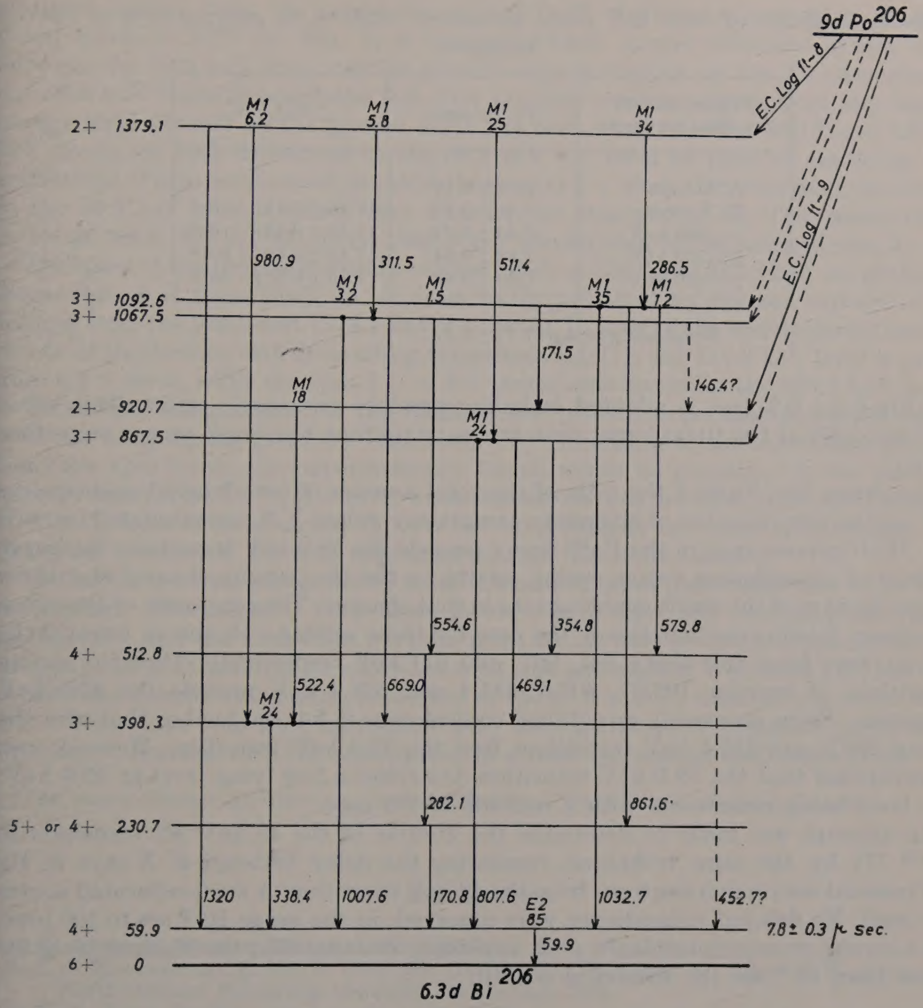

Fig. 5. Decay scheme of Bi^{206}, reproduced with slight changes from reference [1].

relatively small "open time", the individual t_k's were found to depart slightly from the mean value. Corrections for this were made in plotting the delayed coincidence curve. The time scale was calibrated using a Tektronix 517 oscilloscope and a calibration quartz oscillator.

In order to check the position of the 59.9 keV transition in the level scheme of Bi^{206}, reproduced from reference [1] in Fig. 5, the half-life was also measured relative to some higher energy gamma rays from the decay of Po^{206}. Pulses, corresponding to gamma energies higher than about 900, 700 and 450 keV respectively were used to trigger the analyzer. In each case delayed coincidences were obtained. The half-lives from the measurements, calculated by the method of weighted least squares [6], are tabulated in Table 1, where the errors given are statistical. As final value for the

Table 1. Half-life of 59.9 keV state measured relative to gamma rays of various energies.

Trigger pulses for time analyzer	$T_{1/2}$ in μsec	$\sum N_r / \sum N_\gamma$
K X-rays	7.75 ± 0.17	
K X-rays	7.81 ± 0.17	$(7.70 \pm 0.15) \times 10^{-2}$
$\gamma > 900$ keV	7.84 ± 0.71	$(7.16 \pm 0.45) \times 10^{-2}$
$\gamma > 700$ keV	7.82 ± 0.54	$(7.40 \pm 0.30) \times 10^{-2}$
$\gamma > 450$ keV	7.60 ± 0.42	$(7.10 \pm 0.30) \times 10^{-2}$

Weighted average 7.77 ± 0.12.

half-life 7.8 ± 0.3 μsec is adopted including possible systematic errors. This value is of the order of 100 times larger than the estimate from the single proton transition model.

In column 3 of Table 1 the ratio of the total number of real delayed coincidences $\sum N_r$ to the total number of triggering gamma ray pulses $\sum N_\gamma$ are tabulated for each run. If all gamma rays in the Po^{206} decay precede the 59.9 keV transition, the curve of delayed coincidences versus energy setting in the the gamma channel should be a reproduction of the single counting rate in that channel. The constancy of the ratios in column 3 indicates that this is the case for these settings, chosen to contain the gamma rays from and above 981, 807, and 511 keV respectively. Thus the strong transitions of energies 1032.7, 807.6, 511.4 and 522.4 keV precede the 59.9 keV transition. From previously established coincidences it follows further that also the strong 286.5 and 338.4 keV transitions feed the 59.9 keV transition. Hence it can be concluded that the 59.9 keV transition de-excites a low lying level at 59.9 keV; this level being metastable with a half-life of 7.8 μsec.

An attempt was made to determine the lifetime of the 48 keV $E2$ transition in Hg^{198} [7] by the same technique, measuring the delay between K X-rays in Hg and internal conversion electrons from the 48 keV transition. A mass-separated source was used. No delayed coincidences were observed, in the range 10^{-7} sec to 100 μsec, but a strong prompt coincidence peak appeared, meaning that the lifetime probably is less than 10^{-8} sec (cf. Åström *et al.* [8]).

Discussion

On the basis of principles introduced by Pryce [9], a theoretical investigation of the energy levels in Bi^{206} has been made by Wahlborn [10]. By identification of the experimental levels with those theoretically predicted, Wahlborn could give tentative assignments to all levels in the proposed level scheme. The present measurement has unambigously determined the position of the 59.9 keV transition. Furthermore, the ground state spin 6 has recently been established by the atomic beam resonance method [11]. These results, together with previously determined multipolarities and cascade relations [1], permit most probable spin assignments to be made on a purely experimental basis.

Starting with the measured ground state spin and considering that the 920.7 and 1379.1 keV levels should have low spins, as these levels are predominantly fed by electron capture from the even-even nucleus Po^{206}, the spin assignment to the proposed levels in Bi^{206} (cf. Fig. 5) is straightforward. A spin difference of two units between the 59.9 keV level and the ground state is implied by the $E2$ character of the 59.9 keV transition and the fact that no cross over transition from any higher energy level directly to the ground state has been observed. The 920.7 and 1379.1 keV levels are both de-excited to the 59.9 keV 4+ level by pairs of cascading $M1$ transitions. These levels most probably have spin 2+ since the cross over transition to the 59.9 keV level is either very weak or not observed at all. The intermediate levels at 398.3, 867.5, 1067.5 and 1092.6 keV should then all be assigned spin 3+.

The spins of the proposed weakly excited levels at 230.7 and 512.8 keV are probably larger than 3 as these levels do not seem to be populated by electron capture or by feeding from the 920.7 and 1379.1 keV 2+ levels. In view of the multipolarity assignments of the feeding and de-exciting transitions (cf. [1]) the 512.8 keV level is probably a 4+ level, while the spin 5+ or 4+ seems reasonable for the 230.7 keV level.

These spin assignments on the basis of the present experimental results agree with the assignments given by Wahlborn [10]. According to the theoretical predictions low spin levels, not experimentally found, might be populated in the electron capture decay from Po^{206}. However, weak transitions, not included in the level scheme of Fig. 5, have been observed [1]. Further experiments are therefore desirable for extended correlation between experimental and theoretical results.

The levels between which the 59.9 keV transition takes place seem now to be well established. Theoretically both these levels should have the configuration $(p_{1/2})^2$ $f_{5/2}$ $h_{9/2}$ [10], and the transition between them should then be due to a change in spin coupling. It is interesting to note that with this assumption Wahlborn [12] has calculated the gamma transition probability of the 59.9 keV $E2$ transition to about 1500 sec^{-1}. This value is in good agreement with the experimental transition probability 1100 sec^{-1}, derived with the assumption of a total conversion coefficient of 80.

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REFERENCES

1. E. Arbman, Nuclear Physics *3*, 625 (1957).
2. S. A. Moszkowski, p. 391, in Beta- and Gamma-Ray Spectroscopy, edited by K. Siegbahn. North-Holland Publishing Company, Amsterdam 1955.
3. P. A. Tove, Nuclear Instruments *1*, 95 (1957).
4. M. E. Rose, in Beta- and Gamma-Ray Spectroscopy. App IV.
5. F. D. Brooks in Progress in Nuclear Physics V, edited by O. R. Frisch. Pergamon Press, London & New York, 1956.
6. R. Mitchell and R. Madey, UCRL-2783.
7. G. Andersson and I. Bergström, Nuclear Physics *3*, 506 (1957).
8. B. Åström, B. Johansson, and I. Bergström, Arkiv för Fysik *12*, 205 (1957).
9. M. H. L. Pryce, Proc. Phys. Soc. *A 65*, 773 (1952).
10. S. Wahlborn, Nuclear Physics *3*, 644 (1957).
11. I. Lindgren, private communication.
12. S. Wahlborn, private communication.

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